

# Closing the Loop - Haptic Feedback for EMG-Controlled Prosthetics

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This project investigates the design and development of a prosthetic hand controlled using Electromyogram (EMG) signals of the forearm with haptic feedback from sensors on the prosthetic limb. As part of Rose Ridder's Culminating Exercise in Engineering, Ridder designed this system to connect control and feedback mechanisms and integrate four years of engineering study at Swarthmore College. In this project, a simple EMG-controlled, 3D printed prosthetic that provides fingertip pressure-based feedback to the user is prototyped with a material cost of less than \$100.

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## Background

According to the World Health Organization, over 40 million people worldwide are in need of a prosthetic device due to amputation. That number is expected to double by 2050.

With a rising population of people who need them, prosthetics remain hard to attain. Only about 5% of those who need them have access to a prosthetic, and these prosthetics are expensive and often limited in their functionality.

With the rise in maker-culture, prosthetics have been one arena in which cheap fabrication and development is often highlighted. Stories of people making 3D printed limbs are readily available with a simple Google Search, but their performance is limited. Moreover, even the most expensive and complex prosthetics can be limited in their adoption by users. Studies reveal prosthetics are worn only 27% - 56% of the time for upper limb amputees with 43% not using a prosthetic at all[1]. Reasons for this are not well studied, but often relate to issues of function and comfort. Functionality is the most cited reason for reduced prosthetic usage with 33% of respondents citing that as the primary concern. This is followed by issues of fit, cosmetic beauty, and maintenance each at 20% of the respondent pool[2]. Lack of tactile sensation specifically is one of the key rejection reasons for prosthetics [3].

Therefore, research in prosthetics and functions is critical. Increasing their functionality and usability is particularly important as more and more individuals require prosthetics every year, but prosthetics remain expensive and limited in function.

## Introduction

This project is targeted to encompass four years of Engineering Education at Swarthmore College with a focus on electronics, robotics, and biomedical engineering fields. It aims to address the very real problem of developing a cheap, functional, and dynamic prosthetic limb to improve prosthetic adoption and accessibility for amputees. By developing a three-module device (as seen in Figures 2-4 that includes an Electromyogram (EMG) signal acquisition circuit, a prosthetic hand, and a haptic feedback system, this project requires electrical circuitry development, 3D printing tech-

nologies, robotic prosthesis actuation, and integrated system pressure-sensitive button development for generating meaningful signals for haptic vibrotactile feedback. These technologies may be further developed into a single prosthetic device that uses muscle signaling to dynamically control the prosthetic and provide real time touch simulation feedback to the user.

## Muscle Groups

Electromyograms (EMGs) measure the voltage potential across muscles associated with muscle flexing and relaxing. In this project, the focus is upon forearm flexion to control a prosthetic, so the target muscle groups for EMG signal acquisition reside in the forearm. Each finger is controlled by individual and mixtures of multiple muscle contractions which induce a higher voltage potential across the muscle. By measuring the voltage at the center of the muscle and near one end, a voltage difference across the muscle may be measured and processed to control a prosthetic.

Because EMG electrodes are positioned upon the surface of the skin, it is important to select muscles that are superficial rather than deep and have a detectable voltage difference across the muscle.

Figure 1 displays the muscles in the left forearm.

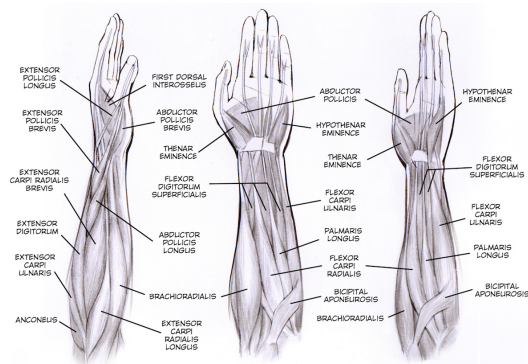


Figure 1. Forearm Muscle Diagram

A contrast-sketch of forearm muscles with the left hand displayed with the palm facing rightward, forward, and leftward[4].

By measuring different muscles around the forearm, we focused our EMG acquisition on the Extensor Digitorum and the Flexor Carpi Ulnaris, which gave the most observable EMG signals for full-hand and individual finger flexing.

## Haptics

Haptics, or the simulation of touch sensations, is a growing field of study as an additional sensory method for perceiving the world around us. Typing on your phone, 4D IMAX movies, and virtual reality are some of the most well-known uses of haptics in today's market. Harnessing the

power of tactile sensory mechanisms provides a unique opportunity to enhance user experience and feedback about a person's environment beyond the other senses of vision, audition, smell, and taste [5].

## Design

The project design is comprised of three modules - an EMG for muscle contraction detection, a prosthetic to control via the EMG with pressure devices to measure contact made by fingertips, and a haptic band to provide feedback to the user based on the prosthetic fingertip sensors.

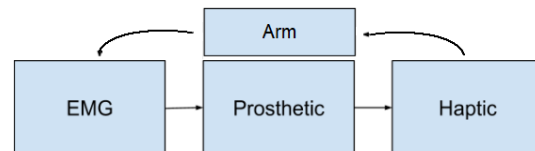


Figure 2. Block Diagram of 3 Modules

A block diagram of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array.



Figure 3. Design Diagram of 3 Modules

Images of diagram of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array as implemented.

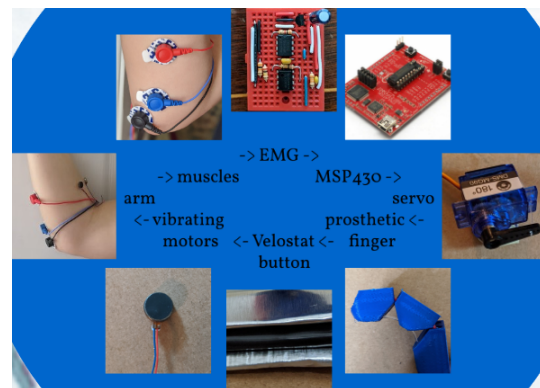


Figure 4. Design Diagram of 3 Modules, in-depth

Images of the critical components of the three modules of this project - the EMG circuit, prosthetic hand, and haptic array as implemented.

## Electromyogram EMG

The Electromyogram (EMG) module consists of a circuit designed to measure voltage potential across the target muscle. By attaching conductive EMG electrodes to the skin,

electrical potential may be measured between two electrodes to detect whether the muscle is flexed or relaxed. This signal is then fed to a circuit composed first of an instrumentation amplifier (INA114) to amplify the voltage difference between two points of the muscle. This amplified signal is then filtered by an active high pass followed by an active low pass filter, creating a band of frequencies that remain in the final signal between 16Hz and 482Hz. These filters are active in order to amplify the signal as they are processed such that through the circuit, the input EMG difference potential has a gain of 30 from the instrumentation amplifier, 6.6 from the high pass filter, and 3.3 from the low pass filter.

The EMG is powered using a 3.6V MSP430 voltage pin as  $V_{cc}$ . There is also a voltage splitter within the circuit to create a virtual ground of  $\frac{V_{cc}}{2} = 1.67V$  which is used to allow all active filters to "invert" the signal around the 1.67V reference point.

In this circuit, the INA114 instrumentation amplifier is used, plus a LFV2772 operational amplifier with two internal op amps for both filters.

The circuit schematic may be seen in Figure 5, and an image of the built circuit is in Figure 6.

The full equipment list may be seen in Appendix Table 2.

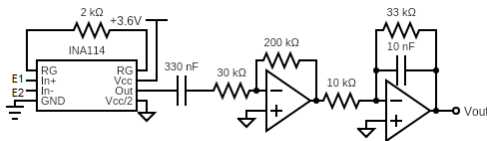


Figure 5. EMG Circuit Schematic

EMG Circuit consisting first of a voltage splitter, an instrumentation amplifier (INA114) and two operational amplifiers

LFV2772 for active filtering of an EMG signal between the frequencies of 16Hz and 482Hz. E1 and E2 indicated leads to Electrodes 1 and 2 placed in the middle of the muscle and at the end of the muscle.

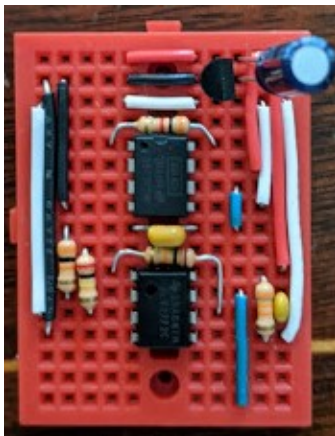


Figure 6. EMG Circuit Image

The built circuit of the EMG signal acquisition and filters.

The output of the circuit is passed to an Arduino Circuit Playground for 60Hz filtering and thresholding. Based on our EMG testing results, the threshold voltage was set at 0.1V which was translated to a digital Circuit Playground Pin. The MSP430 measured this pin and had a threshold of 660 units (on an ADC scale of 1024) to activate the servo motors.

## Prosthetic

The second module of the project design consists of a prosthetic device. This device is a 4-fingered hand-inspired device made of rigid PLA 3D-printed material. Each finger consists of 3 independent rigid sections, resulting in 2 bending joints. Each section of each finger has two large-diameter holes in the exterior side of the finger and one smaller-diameter hole in the interior side of the finger. The 3D print was designed by "grossrc" on Thingiverse [6].

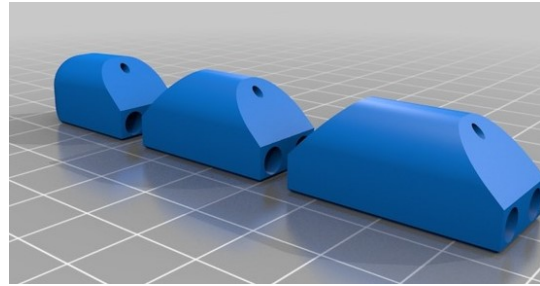


Figure 7. Prosthetic Finger Rendering

Prosthetic Finger Rendering displaying the two larger-diameter holes on the outer finger and the one smaller hole on the inner section.

Through the larger diameter hole are laced two wires connecting the pressure-sensitive fingertip buttons. Through the smaller diameter hole is a nylon microfilament connected to a servo motor horn that allows full compression of the finger joints such that the finger is closed into as tight a circle as the stiff PLA angles allow. By removing the tension on the nylon microfilament, the finger is released toward straight.

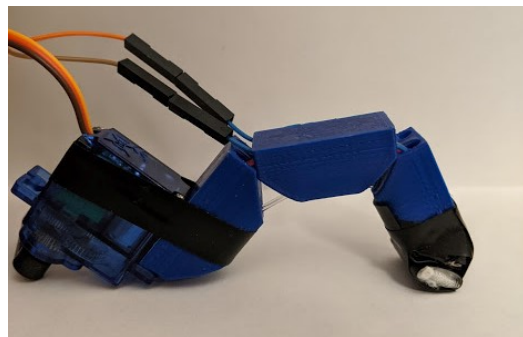


Figure 8. Prosthetic Finger Setup

The built prosthetic finger with wiring and nylon microfilament connections.

The full finger is controlled with one servo motor signalled by the MSP430. An array of fingers may be made to be actuated simultaneously or individual based on the specificity of the EMG differentiation algorithm. In this design deployment, all fingers are activated at once based on the simplicity of the 0.1V thresholding algorithm.

In order to provide appropriate voltage to the servo motor, a level shifter is used to shift provide 5V power to the power input of the signal and a 5V signal with minimal current as supplied by the MSP430 GPIO pins. This circuit incorporated a CD40109B Level Shifter and may be seen in Appendix Section .

The signal to the Servo is a PWM signal from the MSP430 with a base frequency of 50Hz. Adjusting the duty cycle between approximately 5% and 10% controls the servo motor angle.

At the tip of each finger is a pressure-sensitive velostat button. Velostat is a conductive fabric allowing it flexibility and mobility for many uses. Here, the button consists of two squares of aluminum tape, a highly conductive adhesive, each attached to one of the wires in the larger diameter holes of the finger segments. These aluminum squares are separated by the velostat so that they do not conduct electricity in their resting position, as seen in Figure 9. When pressure is applied to the velostat, the aluminum squares make more complete contact with the velostat sheet, which in turn conducts electricity between the aluminum squares and the resistance is lowered. The resistance of velostat pressure element can vary between greater than  $1M\Omega$  and less than  $80\Omega$ , allowing current to reach the next module in the device - the haptic motors. An example force/resistance relationship can be seen in the results section in Figure. 13

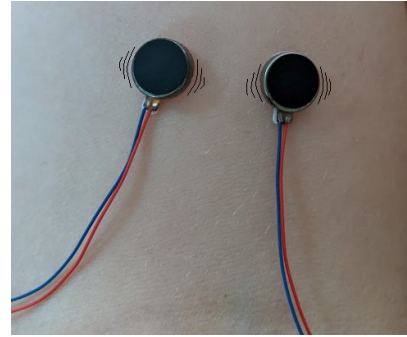


*Figure 9. Velostat Button Design*

Design of the three-layer velostat button used for fingertip pressure sensing consisting of two external layers of aluminum tape sandwiching a piece of conductive velostat. Pressure reduces the resistance of the system, allowing more current to reach the haptic micro motors in module 3.

## Haptic Feedback

The haptic feedback module consists of an array of micro motors that simulate touch feedback at the fingertips, as seen in Figure 10. Based on the pressure measured via resistance on the velostat fingertip buttons, the corresponding micro motors will vibrate in association with the specific fingertip. This allows the user of the prosthetic to sense when enough pressure is applied to perform tasks such as pressing a doorbell, grasping an egg, or closing the fingers together.



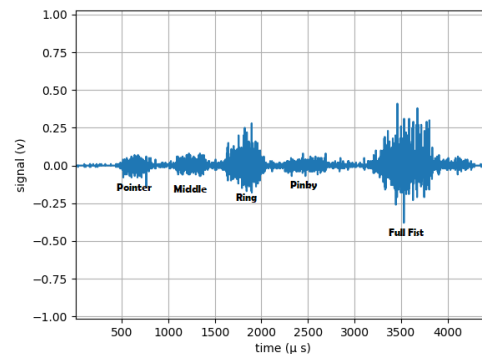
*Figure 10. Haptic Micro Motor Array*

The wearable array of micro motors corresponding to the two fingertip velostat buttons on prosthetic module 2.

## Results

### EMG Waveform

Upon successful development of the EMG circuit, the signal is passed to the MSP430 for processing. Figure 11 displays the filtering and processing that is performed on the MSP430 to identify muscle contraction and therefore signal to close the prosthetic finger.



*Figure 11. MSP430 Processing Diagram*

The filtered signal from electrodes placed on the Flexor Carpi Ulnaris and recorded by the Arduino Circuit Playground.

### Prosthetic Actuation

The MSP430 provides a signal to the appropriate finger's servo motor to close slowly. When the muscle flexion is



halted, the servo motor is halted.

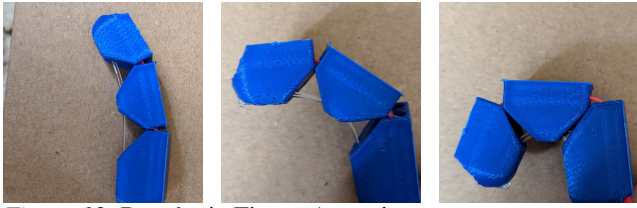


Figure 12. Prosthetic Finger Actuation

Three images of the varying degrees of contraction of the prosthetic finger actuated using a servo motor.

### Pressure Sensitive Curve

The velostat button upon the tip of each prosthetic finger is used to detect pressure on the fingertip. Using this velostat button as a resistor in a circuit, the haptic motors are activated to provide simulated sensory feedback of touch.

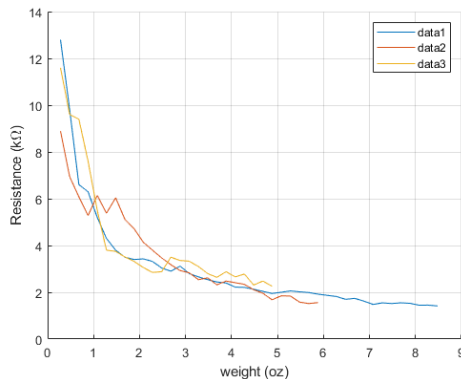


Figure 13. Velostat Button Pressure Response

Plotted relationship between force on the velostat button and resistance of the button.

### Connected EMG Haptic Prosthetic

Two videos displaying the activation of the EMG and the full system with feedback are available at <https://www.youtube.com/watch?v=FYtTcfgnoBk> and <https://www.youtube.com/watch?v=0A-Bv2iPrC8>.

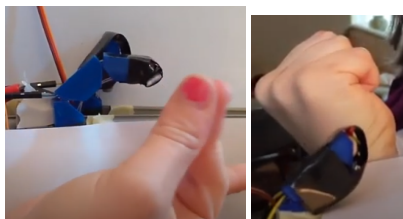


Figure 14. Product Display

Images representing the body-based action that induces actuation of the prosthetic fingers. Upon making contact with the pictured surface, the haptic motor representation of the appropriate contacted fingers vibrates, alerting the user that contact has been made.

### Conclusions

This project displays the successful implementation of a cost-efficient, functional, feedback-driven prosthetic. The EMG circuit is successful in detecting muscle flex differences across a single muscle, the Circuit Playground and MSP430 filter and threshold flexing appropriately, the prosthetic contracts, and the haptic motors convey fingertip pressure information back to the user. All of this was done with a minimal budget, and all supplies used in this design (with both the Arduino Circuit Playground and MSP430) total \$98.73.

### Further Development Opportunities

Further developing this design could be especially rewarding to improve its functionality and cost-efficiency. Particular development opportunities include:

- fully implement design on MSP430
- Better single-muscle flex-detection algorithm
- multiple EMG electrode array
- individual finger flex detection
- individual prosthetic finger activation
- improved prosthetic finger design:
  - including better stabilizing mechanism between fingers, rounded corners, fingertip customization for pressure buttons such as flatter tip or better connection mechanism to avoid bumping from nylon cord knots
- full hand and wrist implementation
- algorithmic fingertip pressure recording
- variable haptic motor activation

## Appendix

## System Materials List

## EMG Full Wire Diagram

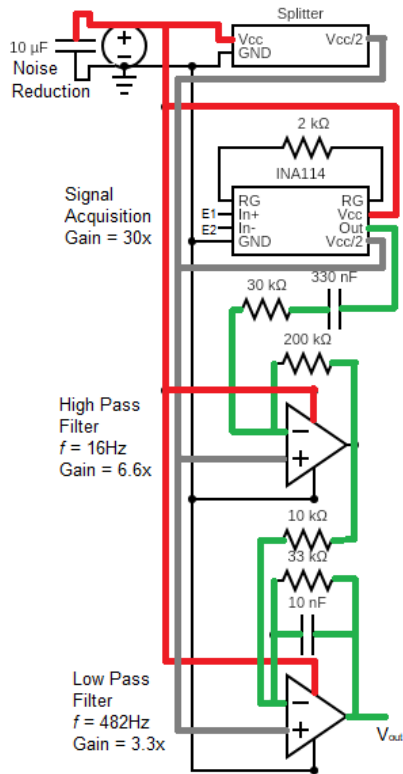


Figure 15. EMG Full Wire Colored Diagram  
Color Coded EMG circuit diagram for assembly purposes. E1 and E2 indicate electrodes 1 and 2.

## Level Shifting Methods

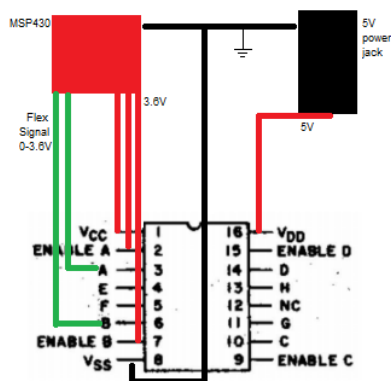


Figure 16. Level Shifting Circuit Diagram  
The diagram for the built circuit for level shifting the MSP430's 3.6V signal to 5V for servo motor activation. The integrated circuit is a CD40109B Level Shifter. Pins A and B are shifted up to 5V and the outputs are E and F for the servo motor activation.

Item	Quantity	Unit Price	Total Price
MSP430G2553	1	\$11.79	\$11.79
Circuit Playground	1	\$17.50	\$17.50
M/F Jumper Wires	1	\$1.95	\$1.95
M/M Jumper Wires	1	\$1.95	\$1.95
F/F Jumper Wires	1	\$1.95	\$1.95
Total			\$35.14

Table 1

Each item is linked to its purchase location

## EMG Materials List

Item	Quantity	Unit Price	Total Price
EMG Leads	1	\$5.00	\$5.00
.01 µF Capacitor	1	\$.30	\$.30
.33 µF Capacitor	1	\$.32	\$.32
10 µF Capacitor	1	\$.84	\$.84
33 KΩ Resistor	1	\$.10	\$.10
10 KΩ Resistor	1	\$.10	\$.10
TLV2772 Op Amp	1	\$2.74	\$2.74
Mini Breadboard	1	\$2.15	\$2.15
Voltage Splitter	1	\$2.66	\$2.66
INA114	1	\$11.56	\$11.56
EMG Electrodes	3	\$15.56/100	\$.47
Total			\$26.24

Table 2

Each item is linked to its purchase location

## Prosthetic Materials List

Item	Quantity	Unit Price	Total Price
PLA 3D printing material	< 100g	\$.06	\$6.00
Aluminum Tape	<1yrd	\$5.00/10yds	\$.50
Velostat	1	\$4.95	\$4.95
5V Power Supply	1	\$7.54	\$7.54
Power Jack Connector	1	\$.77	\$.77
Level Shifter	1	\$.55	\$.55
Mini Breadboard	1	\$2.15	\$2.15
Servo Motor	2	\$5.96/finger	\$11.92
Nylon Cord	25in	\$.50	\$.50
Electrical Tape	20in	\$.50	\$.50
Total			\$35.85

Table 3

Each specialty item is linked to its purchase location.

## Haptic Materials List

Item	Quantity	Unit Price	Total Price
MiniMotors	2	\$0.75	\$1.50
Total			\$1.50

Table 4

The item is linked to its purchase location

## Full Materials List

### Haptics Research Thesis

The background and interest in haptics for this project was inspired by Rose Ridder's Cognitive Science Thesis on the use of haptics for learning and education which may be found in the Swarthmore College Archives.

### Associated Documents and Presentations

- Project Proposal: <https://drive.google.com/open?id=1fNYqynU2cqHjvWfmqYoxyxxRF81jkBoEUxn1AL0QKIM>
- Mid-Semester Presentation: <https://www.youtube.com/watch?v=V7cqG13c7Yk&feature=youtu.be>
- Final Presentation: <https://prezi.com/view/L1SYYjrKWrF3ExpRqN7m>
- Haptics Thesis available on the Swarthmore College Library Thesis Archive.
- Arduino Circuit Playground Code: [https://drive.google.com/open?id=1Ugc04W8JmoZMZqPtkhc\\_7LbYght2rWHv](https://drive.google.com/open?id=1Ugc04W8JmoZMZqPtkhc_7LbYght2rWHv)
- MSP430 code: <https://drive.google.com/open?id=10kC6rd4wgvI0PJrsgQKuJx98tSQysDqj>

### Acknowledgements

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